7-2015

Angular Determination of Toolmarks Using a Computer-Generated Virtual Tool

Ryan Spotts
Ames Laboratory

L. Scott Chumbley
Iowa State University and Ames Laboratory, chumbley@iastate.edu

Laura Ekstrand
Ames Laboratory

Song Zhang
Ames Laboratory

James Kreiser
Illinois State Police

Angular Determination of Toolmarks Using a Computer-Generated Virtual Tool

Abstract

A blind study to determine whether virtual toolmarks created using a computer could be used to identify and characterize angle of incidence of physical toolmarks was conducted. Six sequentially manufactured screwdriver tips and one random screwdriver were used to create toolmarks at various angles. An apparatus controlled tool angle. Resultant toolmarks were randomly coded and sent to the researchers, who scanned both tips and toolmarks using an optical profilometer to obtain 3D topography data. Developed software was used to create virtual marks based on the tool topography data. Virtual marks generated at angles from 30 to 85° (5° increments) were compared to physical toolmarks using a statistical algorithm. Twenty of twenty toolmarks were correctly identified by the algorithm. On average, the algorithm misidentified the correct angle of incidence by −6.12°. This study presents the results, their significance, and offers reasons for the average angular misidentification.

Keywords

forensic science, statistical comparison, computer simulation, algorithm, toolmark, virtual toolmark

Disciplines

Forensic Science and Technology | Materials Science and Engineering

Comments

This is the peer-reviewed version of the following article: Spotts, Ryan, L. Scott Chumbley, Laura Ekstrand, Song Zhang, and James Kreiser. "Angular Determination of Toolmarks Using a Computer-Generated Virtual Tool." *Journal of Forensic Sciences* 60, no. 4 (2015): 878-884, which has been published in final form at DOI: 10.1111/1556-4029.12759. This article may be used for non-commercial purposes in accordance with Wiley Terms and Conditions for Self-Archiving.

Angular Determination of Toolmarks using a Computer Generated Virtual Tool

Ryan Spotts[1], B.S.; L. Scott Chumbley[1*], Ph.D.; Laura Ekstrand[1], M.S.; Song Zhang[1], Ph.D.; James Kreiser[2], B.S.

Iowa State University, Ames Laboratory

Ames, Iowa

[1]Ames Laboratory, Iowa State University, 2220 Hoover, Ames IA 50011

[2]Illinois State Police, Retired, 3112 Sequoia Dr., Springfield, IL 62712

*Corresponding Author

This work was supported by the National Institute of Justice and the U.S. Department of Energy (DOE), Office of Science, Basic Energy Sciences, Materials Science and Engineering Division. The research was performed at the Ames Laboratory, which is operated for the U.S. DOE by Iowa State University under contract number DE-AC02-07CH11358. Funding was provided by award number 2011-DNR-0230 from the National Institute of Justice.

ABSTRACT: A blind study to determine whether virtual toolmarks created using a computer could be used to identify and characterize angle of incidence of physical toolmarks was conducted. Six sequentially manufactured screwdriver tips and one random screwdriver were used to create toolmarks at various angles. An apparatus controlled tool angle. Resultant toolmarks were randomly coded and sent to the researchers, who scanned both tips and toolmarks using an optical profilometer to obtain 3D topography data. Developed software was used to create virtual marks based on the tool topography data. Marks generated at angles from 30 to 85° (5° increments) were compared to the physical toolmarks using a statistical algorithm. Twenty of twenty toolmarks were correctly identified by the algorithm. On average the algorithm misidentified the correct angle of incidence by -5.26°. This paper presents the results, their significance, and offers reasons for the average angular misidentification.

KEY WORDS: forensic science, statistical comparison, computer simulation, algorithm, toolmark, virtual toolmark

Recent history has seen scientific testimony challenged in numerous court cases since the *Daubert v. Merrell Dow Pharmaceuticals, Inc* ruling. In particular, comparative forensic examinations such as firearms and toolmark examination have been increasingly challenged by attorneys due to the perceived subjective nature of the examination and the mistaken impression that there is a lack of scientific studies aimed at addressing its primary assumption, namely, that all tools possess a unique toolmark. Scores of studies have been conducted and published in the Association of Firearms and Toolmark Examiners (AFTE) Journal to validate comparative forensic examination (1, 2), and give credence to the assumption that every tool contains a unique surface topography capable of creating a unique mark if struck against another surface. A number of more recent studies using objective computer-based algorithms have shown toolmarks created by the same tool will statistically be more similar than toolmarks created by similar tools, even when the tools are manufactured sequentially (3, 4, 5). Nichols has written a thorough literature review that responds to many criticisms to forensic examination (1).

The large body of work that currently exists has not stopped judicial challenges, however, since in many instances published studies still rely on what is considered a subjective assessment. Even though current methods have been shown to produce error rates of less than 1% (1), ideally what is desired is an entirely objective analysis that can provide known error rates that are similarly low. Thus, it is necessary for a mathematical tool to be developed to aid examiners in providing more rigorous tool and toolmark identifications that are less subject to charges of subjectivism.

Current research has focused on use of computers and algorithms to increase the robustness of tool-toolmark identifications. Several different approaches have been made. Chumbley has used a nonparametric Mann-Whitney U statistic (referred to as T1) to compare three-dimensional topography data obtained using an optical profilometer (4). Toolmarks made using screwdriver tips at various angles were compared. Results from this study were in agreement with experiential evidence from forensic examiners. T1 values were largest (e.g. increased probability of a matching pair) when toolmarks created by the same screwdriver tip edge and angle were compared. An angular dependence for screwdriver toolmarks was also found by Bachrach et al. (6). It was concluded from this study that screwdriver toolmarks created at different angles can appear to be completely different toolmarks. Specifically, results from this study showed comparisons of screwdriver marks at 15 and 45 degree angles made on the same medium had an error rate of approximately 50%.

Wei, C. et al. has proposed the use of correlation cells for rapid ballistic identifications (7). Correlation cells, select regions on a surface, can incorporate three-dimensional topography data for quick matching between marks. An initial test utilized cartridge cases fired from ten sequentially manufactured pistol slides. Three-dimensional topography data was obtained using a confocal microscope and analyzed under the constraints that three out of three correlation cells must show positive or negative correlation for known and unknown matches respectively to be declared. Initials results of this methodology yielded no false positive or negative identifications.

Petraco has applied machine learning to analyze striation patterns on cartridge cases fired from 9mm Glock pistols and screwdriver marks made in lead (5). A confocal microscope was used to measure three-dimensional topography data from each toolmark. There were 162 profiles measured from 24 Glocks and 290 profiles measured from 58 screwdriver edges (29 screwdrivers) were obtained. Simulated mean profiles based on the real data resulted in 720 total profiles for the Glocks and 1740 total profiles from the screwdrivers were available to be analyzed. Initial algorithmic identifications on subsets of the total collected data found an error rate of 2.5% for the Glock toolmarks with a 95% confidence interval of 1.3 to 3.2% and an error rate of 6.5% for the screwdriver marks with a 95% confidence interval of 3.5 to 10%. Further refinement of the pattern recognition process through increasing the analyzed data sets reduced error rates to 0.03% and 0.01%. The results were good and demonstrated the capability of pattern recognition in toolmark analysis.

The future of forensic comparative evidence undoubtedly leads towards computer-aided forensic examination. The aforementioned studies, and the study to be presented, represent steps along this path. In this study the ability to specifically characterize a tool surface and relate that surface to the mark that tool could be expected to generate under any given set of conditions is demonstrated. The analysis involves a completely objective assessment of the tool surface which is then used to create a computer generated "virtual tool" that can be manipulated at will by the forensic examiner to create any number of "virtual toolmarks". When combined with a statistical algorithm for making comparisons it then becomes possible not only to directly relate a tool to a toolmark but also to predict with a high degree of accuracy the conditions that existed (specifically, angle of attack) when the toolmark was made.

Experimental Methodology

<u>Sample Generation:</u> A blind study was devised where six sequentially manufactured screwdriver tips and one randomly selected screwdriver from another manufacturer (treated as an unknown) were used by a forensic examiner to create a series of 20 toolmarks. Researchers were kept ignorant to the correct tool-toolmark combinations throughout the experiment. Toolmarks were created on approximately 1.5 by 1.5 inch lead plates using the jig shown in Figure 1. Different fixtures allow toolmarks to be made at angles ranging from 30 - 85° in 5° increments. For this study the examiner was instructed to use any angle they wished as well as either side of the screwdriver. This allowed 168 possible combinations of tool and angle used to create marks when both sides of the screwdriver are considered.

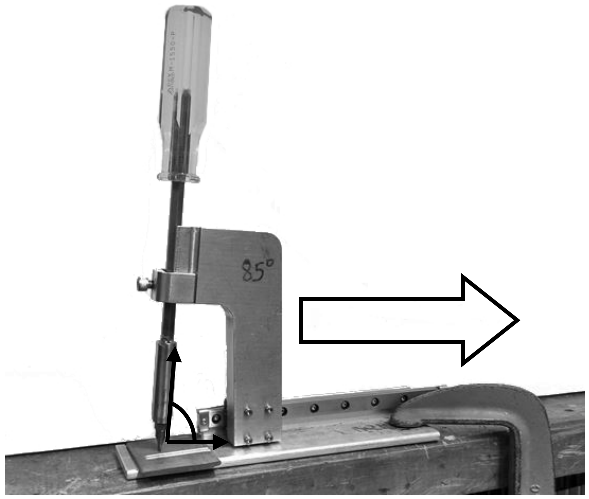


Figure 1: Photograph of jig used to create toolmarks. The 85° angle holder is in use and the direction of the manually applied force is indicated.

No constraints were placed on the creation of the toolmarks. The examiner was free to reuse the same screwdriver and screwdriver edge at two different angles while never using the other edge if he chose to. Ultimately twenty toolmarks were made. Toolmarks were labelled with randomly generated three digit ID tags and sent to the research group. An answer key containing the correct combinations of tool-toolmarks were kept in a sealed envelope until the research group presented their identifications.

Surface Characterization: After receiving the tools and toolmarks, the surface topography was obtained from the six screwdriver tips and the created toolmarks using an optical profilometer (Alicona InfiniteFocusSL). This equipment employs focus variation to scan and obtain accurate three-dimensional topography data. Focus variation works through a precisely controlled z-axis that is able to bring varying portions of the surface into focus. When an object is in focus, the object sharpness (function of light returned to sensor) is at a maximum. The sharpest data for each pixel then is used to construct the three-dimensional topography (8). An approximately 2x7 mm^2 area of topography data were obtained from each toolmark. Toolmark areas were visually selected from representative areas of the entire toolmark having the most complete sections of the entire toolmark. Data were obtained by scanning from edge-to-edge. An example of one lead plate with a labeled toolmark showing the area scanned is shown in Figure 2.

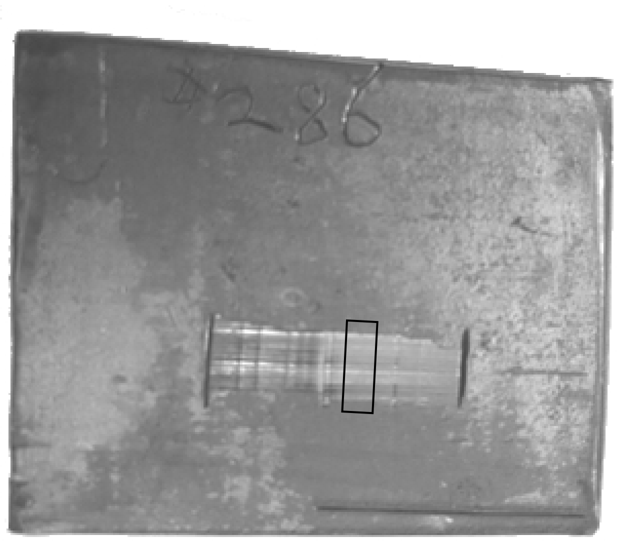


Figure 2: Example toolmark used in the study.

Each side of the screwdriver tips were scanned at a 45° angle relative to the vertical axis of the infinite focus microscope objective. An apparatus was used to hold the screwdriver tips at precisely the same angle for each scan. Figure 3 shows an example of the portable scanning equipment and the apparatus holding a screwdriver tip.

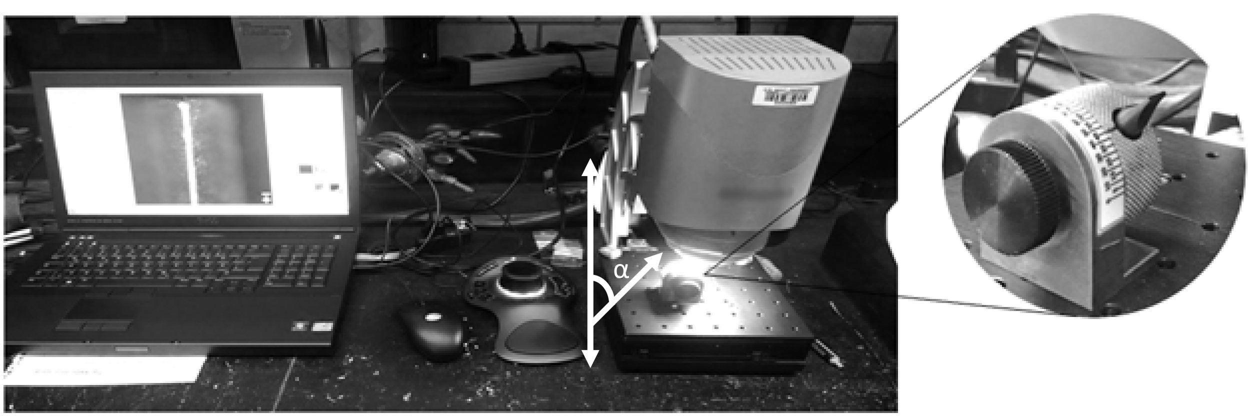


Figure 3: Scanning equipment and apparatus for holding screwdriver tip (45˚ angle defined).

Each data set (from both toolmark and screwdriver tip) had a horizontal pixel resolution of 3.914 µm and vertical resolution of 1.007 µm. Scans were completed at a 10x magnification. Approximately 5 minutes were needed to obtain data from each sample.

Noise Reduction: Any method of automated data collection will contain noise due to random variables. In using an optical system noise can be generated by imperfections (e.g. artifacts such as small spikes or holes) that greatly alter the normal scattering of light collected from the surface that is used for generating an image. To fix this issue and to eliminate unneeded data a cleaning procedure is required.

Before an automated statistical algorithm can be used the operator must ensure that the data to be compared only contains information relevant to the comparison. For example, Figure 4 shows the complete scan obtained from a toolmarked surface. Since the goal is to compare the toolmark, not the unmarked surface of the lead plate on which the mark is made, extraneous data at the edges of the scan must be removed. Software named Mask Editor was developed to allow manual cleaning of each data set. A “painting” tool allows the user to manually paint over (mask) areas of unneeded data without altering the data itself; painted regions are simply ignored in further analysis. The software is programmed to find the largest contiguous unmasked region, so the masking process is not tedious.

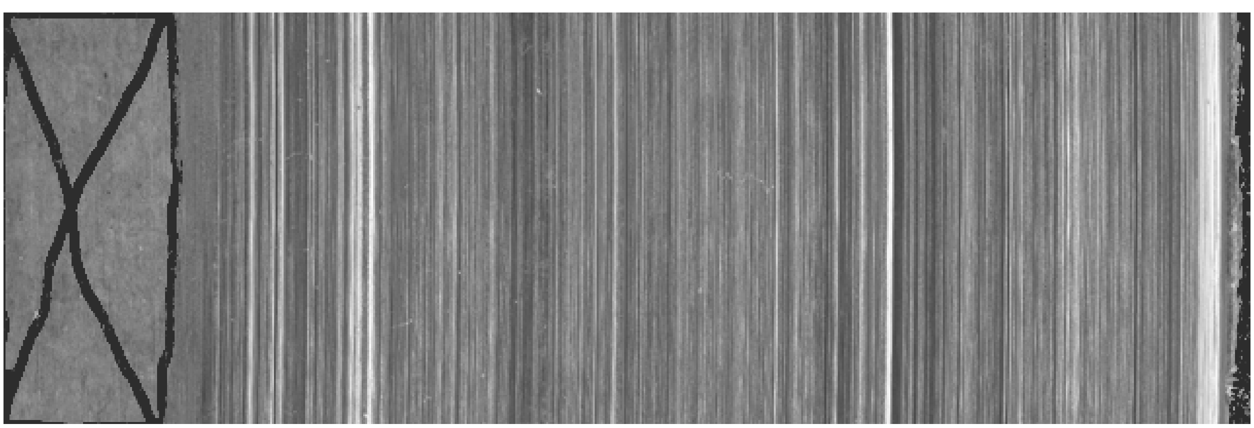


Figure 4: Toolmark 556 (dimensions approximately 7x2mm) during masking process

After masking, spike artifacts on the screwdriver tips are dealt with through the use of a seventh-order polynomial that was applied to each row and column within a data set. Any data points with a depth 100 μm greater or less than the predicted value were removed. This threshold was determined through experimentation. Any small holes (20 pixels or less in diameter) in the data were then filled using linear interpolation. Toolmarks were detrended to remove small angular differences (relative to the z-axis of the optical profilometer) that occur when scanning multiple samples (9).

Data Comparison: Once cleaned, the data sets were suitable for comparisons using a developed software suite and the previously developed algorithm (4). Termed the Mark ANd Tool Inspection Suite (MANTIS) this software is being developed to allow comparisons of toolmarks to actual marks or virtual marks generated from three-dimensional tool topography. A full overview of the virtual mark generation procedure is given in (10), and the reader is directed there for complete technical details. Briefly, the software uses the tool data set that was scanned and cleaned at a known angle. The data can then be rotated to any angle one wishes to investigate. 2D cross-sections at the relevant angle are analyzed across the tool and highest topographical points at the relevant angle are used to construct a virtual "effective" topography profile. Figure 5 shows this process for a generic example schematically.

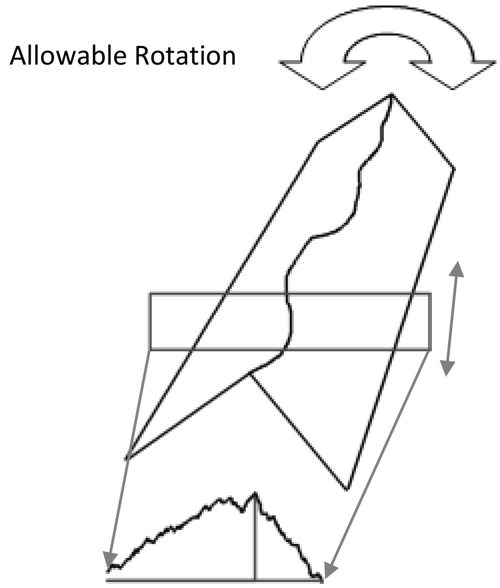
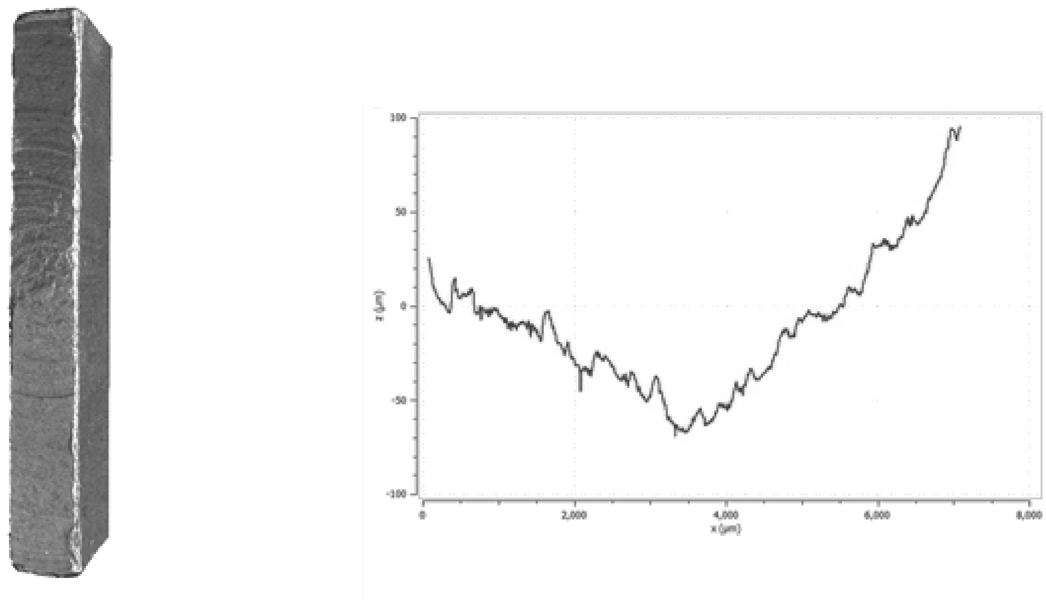


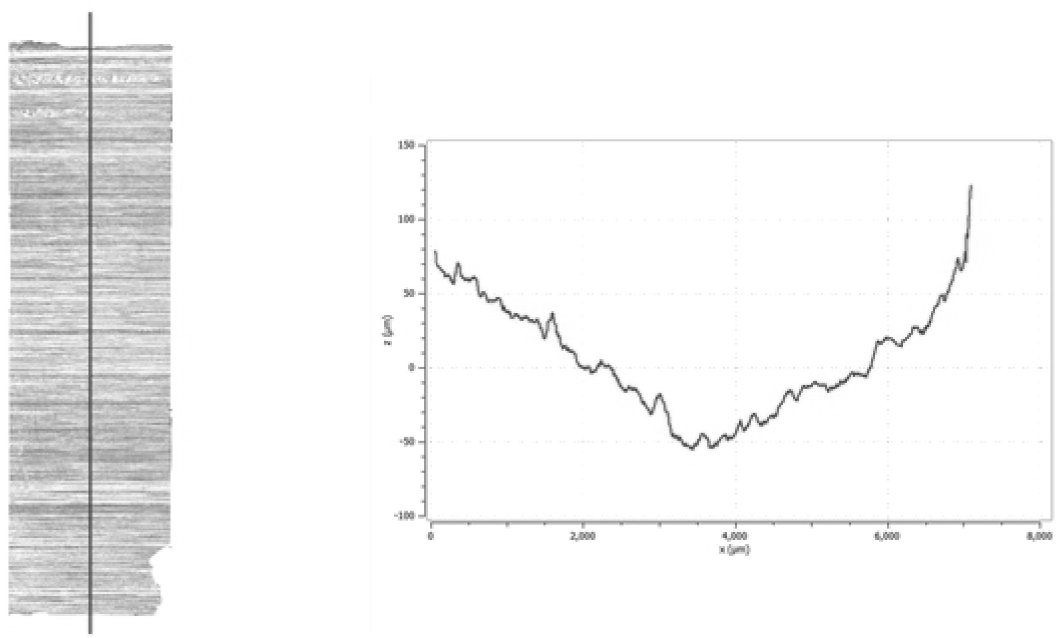
Figure 5: Generic screwdriver tip with highest topographical point found for one cross section

The reasoning for this is that the highest points are assumed be the first points to contact another surface and, therefore, are the primary cause of the striae observed in a toolmark. This effective virtual tool topography is “dragged” against a virtual substrate at the relevant angle to generate a virtual toolmark. The topography of the virtual toolmark is what is compared to the physical toolmark. The process virtually mimics the actions performed by a forensics examiner – using a test mark created by marking a substrate with a suspect tool to compare to an evidence mark. This first level approximation does not account for material properties, applied force or the other two rotation axes; it was assumed the effective topography was fully transferred and the virtual mark resulting from this process is basically the inverted effective tool topography. (N.B. The complexity of the virtual marking process will allow for higher level approximations where the sliding action of the virtual tool against the virtual substrate has a large impact on the results.)

Figure 6 shows an example of a virtual toolmark created by characterizing the tooltip as compared to data obtained from the corresponding physical toolmark. The solid line crossing the physical toolmark represents the path trace that produced the profile data shown.



a.



b.

Figure 6: a) Virtual mark generated at 75°. b) Corresponding physical toolmark created at 75°.

The MANTIS software was used to generate virtual toolmarks at angles from 30 to 85° at 5° increments for each screwdriver tip and perform comparisons to physical toolmarks using the statistical algorithm discussed in (4). For this study three combinations of user-determined parameters were used. Multiple parameter sets were used to see if the results varied due to different user-input. Parameters that were varied include the pixel widths of search and validation windows as shown in Table 1.

Parameter Set	Search Window	Validation Window
1	500	200
2	500	500
3	800	800

Table 1: Algorithm input parameters

The algorithm outputs a single T1 statistic for each comparison. Three parameter combinations, twelve angles, twelve effective screwdriver tip edges (N.B. the unknown screwdriver was not examined) and twenty toolmarks led to 8,640 T1 values. Based on observations in (10, 3, 4), a maximum T1 value is expected to occur when there is a statistical likelihood of a match. This will only occur if the correct combination of virtual mark, angle and toolmark are compared. The T1 value is also expected to decrease as comparisons are made of similar marks made at angles varying by greater than 10˚ are compared (4, 11).

A heuristic critical value was used to determine whether the T1 output corresponded to a matching tool-toolmark combination. It is known that for matching pairs, the statistical distribution of T1 depends on many factors, and cannot be derived analytically based on what is currently known. For nonmatching pairs, observations show that the distribution of T1 is closer to that suggested by simple theory (approximately normal with zero mean and unit variance), but cases have occurred where this does not agree with experimental data. Hence for this study, a value was heuristically chosen. A T1 value greater than 6 was heuristically treated as the critical identification criteria – If the standard asymptotic distribution theory held, this would correspond to incorrectly identifying a nonmatching pair as matching with an extremely low probability. The toolmark and creation angle were identified as matching by the maximum T1 value above the critical value.

Experimental Results

Figure 7 shows the identification process graphically using both matching and nonmatching tool-toolmark combinations from the results of this study. For reference, screwdriver tips are named using a simplified scheme (e.g. T20A where the number can range from 20 to 25 for the 6 different tips and either an A or B is present to differentiate between the two tool edges) and toolmarks were named using randomized 3 digit ID codes. T1 values from this example show the nonmatching pair fluctuated between approximately -4 and 3, but never above the critical value of 6 – consistent with a nonmatching comparison. The shown matching pair T1 values were above the critical value from 30 to 45° with the maximum value occurring at 35°. These results would indicate that the algorithm had identified toolmark 408 as being created by screwdriver tip T20A at 35°. The algorithm was able to identify the correct tool-toolmark combination over an angular range of -5 to +10° (30 to 45°). This methodology was repeated for each parameter set over all possible combinations to determine the matching pairs.

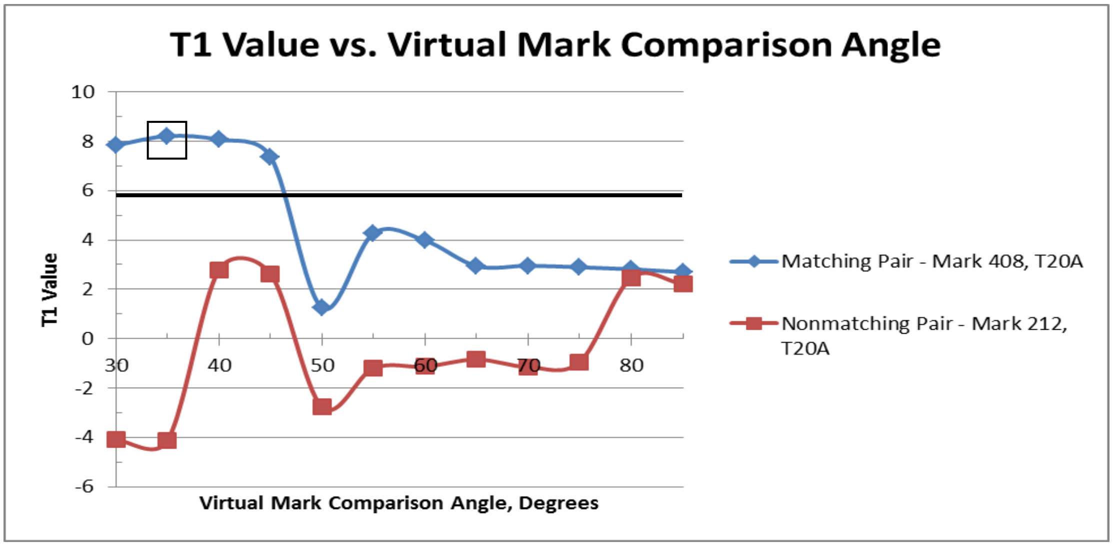


Figure 7: Statistical output using Parameter Set 2 as a function of angle.

Results from the identifications are shown in Table 2. Utilizing only the algorithm and virtual marking, every toolmark (20/20) was correctly paired with the screwdriver tip edge that created it, with toolmarks from the additional unknown screwdriver being identified through exclusion. No false positives occurred during identifications. On average the maximum T1 value occurred at an angle 5.26 degrees less than the answer key creation angle. The average range in Table 2 refers to the average angular range that the algorithm was able to identify matching tool-toolmark combinations – for parameter set 3 the algorithm identified matching tool-toolmark combinations on average from 11.7° less than the maximum T1 value to 13.6° greater than the maximum T1 value. This means the algorithm calculated a T1 value greater than the critical value over a total range of 25.3 degrees.

Screwdriver Identification					
Toolmark	Answer Key	Parameter 1	Parameter 2	Parameter 3	Avg. Angle Mismatch (°)
420	T23B at 75°	T23B at 70°	T23B at 70°	T23B at 70°	-5.0
408	T20A at 40°	T20A at 35°	T20A at 35°	T20A at 35°	-5.0
787	T24A at 55°	T24A at 45°	T24A at 45°	T24A at 45°	-10.0
556	T22B at 65°	T22B at 55°	T22B at 60°	T22B at 60°	-6.7
621	T21A at 45°	T21A at 35°	T21A at 35°	T21A at 35°	-10.0
983	T25A at 45°	T25A at 35°	T25A at 35°	T25A at 35°	-5.0
872	T20B at 60°	T20B at 55°	T20B at 55°	T20B at 55°	-5.0
648	T25A at 60°	T25A at 55°	T25A at 50°	T25A at 55°	-6.7
552	Unknown at 30°	No match	No match	No match	-
514	T22A at 30°	No match	No match	T22A at 30°	0.0
416	T23A at 70°	T23A at 60°	T23A at 65°	T23A at 65°	-6.7
916	T21A at 70°	T21A at 60°	T21A at 60°	T21A at 60°	-10.0
409	Unknown at 70°	No match	No match	No match	-
423	T24B at 80°	T24B at 70°	T24B at 70°	T24B at 70°	-10.0
212	T20B at 80°	T20B at 75°	T20B at 75°	T20B at 75°	-5.0
394	T25B at 40°	T25B at 35°	T25B at 35°	T25B at 35°	-5.0
674	T21B at 40°	T21B at 35°	T21B at 30°	T21B at 30°	-8.3
448	T24B at 40°	T24B at 40°	T24B at 40°	T24B at 35°	-1.7
286	T23B at 40°	T23B at 35°	T23B at 40°	T23B at 35°	-3.3
616	T22A at 75°	T22A at 75°	T22A at 75°	T22A at 70°	-1.7
Avg. Range		-7.6°, +9.4°	-11.8°, +12.4°	-11.7°, +13.6°	Avg. Mismatch -5.26°

Table 2: Tabulated results from the study

Discussion

Correctly identifying every toolmark provided validation of both the comparison algorithm used and the ability to create a virtual toolmark that accurately reflects what can be expected in real life. These results open up a number of possibilities for the future use of virtual markings, both in the area of basic science and applied research.

Although initial results are promising, deficiencies were observed in the results. The first deficiency is the clear bias of the maximum T1 value occurring at lower angles than the creation angle. Deflection of the jig was investigated as the potential cause since the direction of deflection would naturally lower the true creation angle. Figures 8 - 10 show photos captured from slow motion video recorded while creating additional toolmarks. The deflection was measured using photo imaging software on the photographs for toolmarks created at 30, 55 and 85°. Measurements revealed a deflection of approximately 2 to 4° can occur during toolmark creation caused by movement of the screwdriver tip in the holder and not deflection of the screwdriver tip holder. However, a 2 to 3° deflection during toolmark creation explains much of the apparent angular bias in the results. Since virtual marks were compared to toolmarks in 5° increments, and a 3° deflection occurring during toolmark creation was possible, it is not surprising that the virtual mark 5° less than the nominal creation angle would have higher correlation to the toolmark.

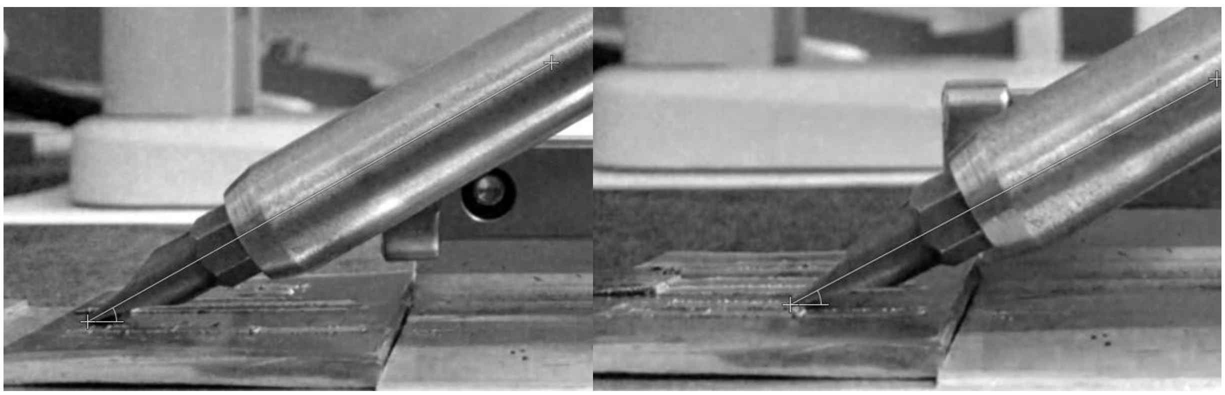


Figure 8: Before and during toolmark creation, measured angles of 29.5° and 27.8° respectively

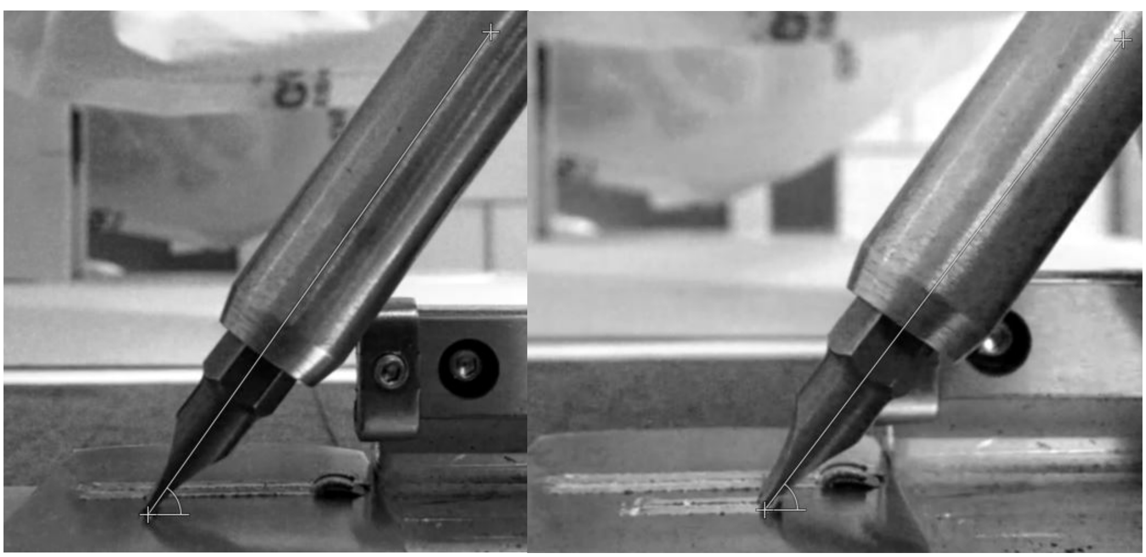


Figure 9: Before and during toolmark creation, measured angles of 54.6° and 52.8° respectively

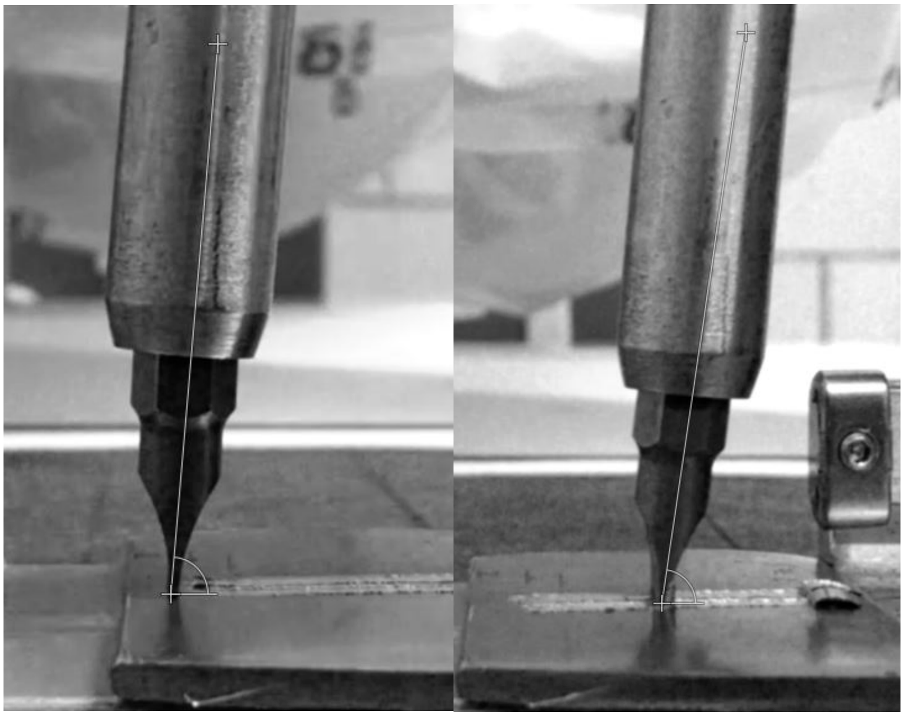


Figure 10: Before and during toolmark creation, measured angles of 85.1° and 81.6° respectively

The second deficiency was observed with Toolmark 514. Two parameter settings failed to identify Toolmark 514 (two false negatives). Since this toolmark was nominally created at 30°, and compared to a 30° virtual mark, it was thought that deflection may have played a role in this lack of identification. Toolmark 514 was compared to a 25° virtual mark; however T1 values were still well below the critical value for the two parameter settings. Inspection of the data revealed that for parameter settings 1 and 2, the regions of highest correlation were found between two prominent topography features that were not actually related. The larger sized parameter setting 3 was large enough to distinguish between the prominent topography features – resulting in the correct identification of the tool-toolmark combination. In other words, careful examination of the data is necessary when conflicting results are obtained for different parameter settings to ensure that the computer is truly conducting a valid comparison.

The final deficiency investigated were instances where the maximum T1 value occurred when the angle was 10° lower than the creation angle, as occurred for toolmarks 787, 621, 916 and 423. Algorithm output variation was investigated as a possible cause of this deficiency in the results. The comparison algorithm utilizes random number generation during analysis to select toolmark profile regions for correlation computation (4). Due to the use of random numbers the same T1 value is not computed for repeated comparisons – there is a small amount of output variation.

To test this, Toolmark 787 and its corresponding screwdriver tip T24A were used for repeated comparisons. Toolmark 787 was created using a 55° holder. However the maximal T1 value was computed at 45°. To determine whether output variation was the potential cause of an additional 5° of error after error due to deflection, 50 comparisons were performed using Parameter Set 2 at 45, 50 and 55°. The results are presented in Figure 11 using box plots. The box plots are composed of a solid black line representing the median value, boxes representing the 1st and 3rd quartiles (bottom and top of the box respectively), whiskers representing a maximum of 1.5 times the interquartile range and circles to represent outlier data points. The box plots show complete separation of each measurement, indicating output variation is not a likely cause of this deficiency.

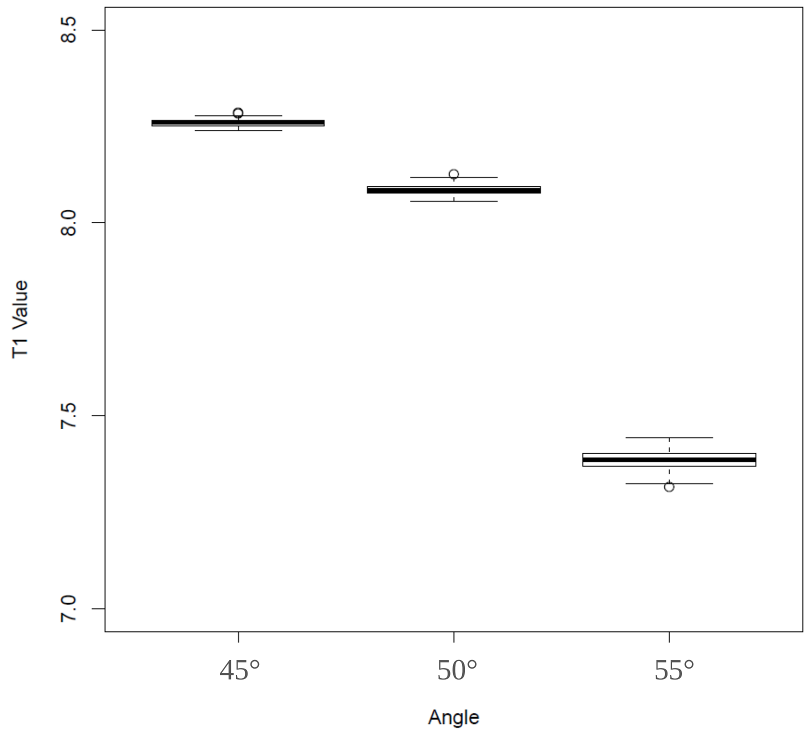


Figure 11: Output variation of repeated comparisons.

While every attempt is made to control the creation of the toolmarks, there are inherent fluctuations in the applied force during toolmark creation. Fluctuations in applied downward force are caused by the relative alignment of the jig to the lead plate. The screwdriver will not be aligned perfectly within the jig before each use and the lead plate thickness varies between samples (lead plates were purchased at the same nominal thickness). These factors result in fluctuations of the applied force and ultimately the topography of the created mark. This inherent variation may be the cause of some of the observed error.

Summary and Conclusions

Twenty out of twenty tool-toolmark combinations were correctly identified, and the marking angle reasonably estimated, in a blind study comparing virtual toolmarks created by analyzing a tooltip to actual toolmarks by means of an objective statistical algorithm. On average virtual marking estimated the angle of creation within approximately 5° of the true angle of creation. The results from this study indicate that toolmarks are best identified when made within approximately 10° of each other to be correctly identified using the employed algorithm.

Deficiencies in the results were addressed. The heuristically chosen critical T1 value, while useful, is not entirely defensible due to the dependence of the matching pair T1 statistical distribution on input parameters. It was also found that 2 to 3° of deflection occurs during toolmark creation. The deflection was the root cause of some of the estimated angular inaccuracy. If 3° of deflection occurred during toolmark creation, it is expected that the virtual mark 5° lower than the nominal creation angle would have higher correlation to the toolmark. In instances where the maximal T1 value occurred at an angle 10° off of the nominal creation angle it was found that inherent variation of the calculated T1 values was not a factor. It is likely that 5 of the 10° is due to deflection while the remaining 5° of angular mismatch was possibly due to inherent variation of the applied force during toolmark creation.

This study provided validation for the concept of creating "virtual toolmarks" as an aid in the identification process by directly relating a tool to a mark and in allowing determination of certain parameters related to the marking. Evidence supporting the anecdotal statements of forensic examiners stating that a fixed angular range exists over which toolmark identifications can occur was found. Virtual marking could ultimately serve as a useful tool to aid forensic examiners in more accurately estimating toolmark angles, as a training tool, and in obtaining basic information concerning perception of what does or does not constitute a match. Finally, this study provided further validation of the primary assumption of comparative forensic examination, namely, that even sequentially manufactured tools contain identifiably unique topographies.

Acknowledgments

The research group thanks the Omega Company for supplying sequentially manufactured screwdriver tips. Without help from companies such as Omega, this research would not be possible. The research group also thanks Dr. Max Morris for his manuscript review and technical guidance.

References

1. Nichols RG. Defending the scientific foundations of the firearms and tool mark identification discipline: responding to recent challenges. J Forensic Sci 2007; May;(52)3:586–594.
2. Hamby JE, Thorpe J. The history of firearm and toolmark examination. FirearmsID LLC. http://www.firearmsid.com/A_historyoffirearmsID.htm (accessed Jan. 29, 2014).
3. Faden D, Kidd J, Craft J, Chumbley LS, Morris M, Genalo L et al. Statistical confirmation of empirical observations concerning toolmark striae. AFTE Journal 2007;39(3):205-214.
4. Chumbley LS, Morris M, Kreiser J, Fisher C, Craft J, Genalo L et al. Validation of toolmark comparisons obtained using a quantitative, comparative, statistical algorithm. J Forensic Sci 2010; May;55(4):953-961.
5. Petraco N DK, Kuo L, Chan H, Phelps E, Gambino C, McLaughlin P et al. Estimates of striation pattern identification error rates by algorithmic methods. AFTE Journal 2013;45(3): 235-244.
6. Bachrach B, Jain A, Jung S, Koons R. A statistical validation of the individuality and repeatability of striated toolmarks: screwdrivers and tongue and groove pliers. J Forensic Sci 2010; Mar 55(2): 348-357.
7. Wei C, Tong M, Song J. Validation tests for the Congruent Matching Cells (CMC) method using cartridge cases fired with consecutively manufactured pistol slides. AFTE Journal 2013;45(4):361-366.
8. Alicona Imaging GmbH. FOCUSvariation. English edition, 2013/14; http://issuu.com/alicona/docs/alicona_focusvariation_edition_4 (accessed Nov. 20, 2013).

9. Zhang S, Ekstrand L, Grieve T, Chumbley LS, Morris M. Three-dimensional data processing with advanced computer graphics tools. SPIE Optics and Photonics, San Diego, California (2012)
10. L. Ekstrand, S. Zhang, T. Grieve, L. S. Chumbley, and J. Kreiser. Virtual tool mark generation for efficient striation analysis. J Forensic Sci. In press.
11. Lock A, Morris M. Significance of angle in the statistical comparison of forensic tool marks. Technometrics 2013; 55(4): 548-561.

Additional information and reprint requests:

Scott Chumbley, Ph.D.

Materials Science and Engineering Department

Iowa State University

2220 Hoover

Ames, Iowa 50011

Email: chumbley@iastate.edu